The Flow and Fracture of Cracked Ice: Experiments to Aid Modeling

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LONG TERM GOALS

The ultimate goal of this work is to contribute new physical insight to the development of the next generation sea ice model, "PIPS 3.0". More specifically, it is to understand the processes underlying the deformation of first-year sea ice covers, from the formation of oriented leads to the frictional sliding of individual floes.

OBJECTIVE

The objective is to test the hypothesis that first-year sea ice covers deform through a combination of continuum and granular flow. It is suggested that continuum flow controls deformation until "slip lines" develop, at which point granular flow governs. With this in mind, the near-term objectives are to study and understand the mechanical behavior of columnar sea ice deformed in the laboratory under controlled conditions and then to compare behavior on the small scale with that on the large scale. The second hypothesis to be tested is that the physical processes underlying the compressive failure of ice are independent of spatial scale.

APPROACH

Deformation experiments on both the laboratory (sub-meter) and the intermediate/engineering (meter) scales are underway. A study is being made of the mechanical behavior of meter-sized blocks of ice grown under natural conditions and of the behavior of smaller specimens harvested from the larger blocks. The material is characterized by columnar grains whose crystallographic c-axes are randomly oriented within the plane of the sheet, as in natural first-year sea ice covers. The blocks are being loaded under compression at controlled strain rates. The experiments are being performed using a novel loading frame installed outdoors in a pond at USA-CRREL. In parallel with the lab experiments, satellite images of the sea ice cover are being examined for lead patterns. Also, in collaboration with W. D. Hibler, III models of the failure process are being developed.

WORK COMPLETED

A second set of experiments using the outdoor facility was completed during the winter of '99, plus a comparative set of lab experiments on the compressive failure of material from the same source. Within the experimental scatter, there is no evidence of an effect of specimen size on either the ductile or the brittle compressive failure stress of S2 saline ice, at least over the range of size from ~0.1 to 1 meter. The work is being prepared for publication.

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A preliminary examination of satellite images has extended the view, first expressed by Schulson and Hibler (1991) following observations of wing-like cracks in the ice cover of the Beaufort Sea, that the physics of failure may be independent of spatial scale. The observations are being included in a review paper on the brittle failure of ice currently in preparation by the author.

In collaboration with W. D. Hibler, III work has been completed on the development of an anisotropic sea ice model to describe the formation of oriented leads or "slip lines". A manuscript has been accepted for publication in Journal of Geophysical Research.

RESULTS

Twelve additional experiments (totaling 26) were performed in the CRREL pond on 0.16 m thick blocks one meter on edge loaded under uniaxial compression at strain rates from 10^{-5} s^{-1} to 10^{-2} s^{-1} at temperatures close to the melting point. Also, 15 experiments were performed in the laboratory on cubes 0.15 m on edge, harvested from the same source and deformed at essentially the same temperature (~-3°C) and over the same range of strain rate. The experiments confirmed that independent of size the ductile-brittle transition occurred at a strain rate of 10^{-3} s^{-1}. Analysis of the complete set of ductile compressive strengths showed strain rate sensitivity m=0.19 ($\sigma\ \alpha\ \square$), in reasonable agreement with values obtained from smaller specimens and with the literature (Kuehn and Schulson, 1994;Timco and Frederking 1986). The results offer no evidence for an effect of size per se on either the ductile or brittle compressive failure of saline ice, over the range investigated.

In addition to features (Schulson and Hibler 1991) that resemble wing cracks generated in the laboratory, satellite images reveal sets of interescting leads (e.g., Figure 2 of Marko and Thomson 1977; Figure 2 of Kwok et al. 1999) that resemble small-scale brittle compressive shear faults (Figure 2 of Schulson et al. 1999) plus crack patterns (e.g., Figure 7 of Erlingsson 1988) that resemble comb cracks generated in the laboratory (Figure 2 of Schulson et al. 1999). The in-pack stress (compressive) under which the field features may have formed was estimated from wing crack and comb crack mechanics to be between ~3 and 30 kPa. This estimate is similar in magnitude to the range of in-pack compressive stress (10 to 100 kPa) measured by Coon et al. (1989), by Tucker and Perovich (1992) and by Richter-Menge and Elder (1998). The field stresses are about three orders of magnitude lower than failure stresses in the laboratory because the brittle compressive failure stress scales as $\lambda^{-0.5}$, where λ is the length of the stress concentrator and the concentrators in the field (thermal cracks, refrozen leads) are about six orders of magnitude larger than in the lab (i.e., km vs mm). The "look alike" features plus the rationalization of the failure stresses suggest that the physics of failure are scale independent. Supporting this suggestion are the results of a recent fractal analysis by Weiss (1999) of the fracture and fragmentation of ice on over nine orders of magnitude of spatial scale (10^{-4} to 10^{5}m).

IMPACT/APPLICATIONS

As noted in Progress Report '98, the results are impacting the development of the numerical modeling of the flow and fracture of anisotropic sea ice and of lead formation. With "PIPS 3.0" in mind, collaboration continues with W.D. Hibler, III and has been initiated with J.Richter-Menge and J.Overland.

TRANSITIONS

The foregoing results were presented during a PIPS 3.0 Development Team Meeting, National/Naval Ice Center, Washington, July 14-15, 1999.

RELATED PROJECTS

Closely related to this project is one by W.D. Hibler under a separate ONR grant N00014-97-1-0381. He is numerically modeling the fracture and flow of anisotropic (cracked) sea ice.

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